On the Economic Value of Seasonal-Precipitation Forecasts: The Fallowing/Planting Problem

Barbara G. Brown[1], Richard W. Katz[2], and Allan H. Murphy[3]

Abstract

The so-called fallowing/planting problem is an example of a decision-making situation that is potentially sensitive to meteorological information. In this problem, wheat farmers in the drier, western portions of the northern Great Plains must decide each spring whether to plant a crop or to let their land lie fallow. Information that could be used to make this decision includes the soil moisture at planting time and a forecast of growing-season precipitation. A dynamic decision-making model is employed to investigate the economic value of such forecasts in the fallowing/planting situation.

Current seasonal-precipitation forecasts issued by the National Weather Service are found to have minimal economic value in this decision-making problem. However, relatively modest improvements in the quality of the forecasts would lead to quite large increases in value, and perfect information would possess considerable value. In addition, forecast value is found to be sensitive to changes in crop price and precipitation climatology. In particular, the shape of the curve relating forecast value to forecast quality is quite dependent on the amount of growing-season precipitation.

1. Introduction

Many of the decisions that farmers make on a regular basis have consequences that depend in part on unknown future weather events. For example, grain farmers must decide each year what crop to plant, with some grains requiring more water than others to grow successfully. Such agricultural decisions require information about the weather over an entire season—the upper limit of the time horizon of forecasts currently issued by the National Weather Service (NWS). Thus, seasonal forecasts could, at least potentially, be used to make more effective decisions of this type.

One possible application of seasonal forecasts relates to the practice of fallowing in the production of spring wheat in the northern Great Plains region of the United States and in adjacent regions of Canada. In the drier, western-most portion of this region (e.g., western North Dakota and eastern Montana), many farmers routinely grow a crop every other year, leaving the land fallow in alternate years. The primary reason for fallowing of dryland wheat is to attempt to insure that sufficient moisture will be available at planting time the following year to grow an economically viable crop.

In recent years farmers have sometimes deviated from the fixed strategy of planting a wheat crop every other year by omitting a fallowing period (i.e., by practicing continuous cropping) when the soil moisture at planting time is deemed adequate (Brown et al., 1981). In addition to soil moisture at planting time, growing-season precipitation is the primary variable that determines spring-wheat yields in semi-arid regions such as the northern Great Plains (Baier, 1972). Currently the only information about growing-season precipitation that the farmers apparently use in making the fallowing/planting decision consists of climatological probabilities; that is, information based on historical weather records (Brown et al., 1981). Hence it seems reasonable that these farmers could use a forecast of growing-season precipitation, if a forecast in the appropriate form was available, in deciding whether or not to plant a crop. In this regard, the NW currently produces 30-day and 90-day precipitation outlooks on a bimonthly and monthly basis, respectively.

This paper describes a specific case study of the economic value of seasonal-precipitation forecasts in the fallowing/planting decision-making situation. Because of the dependence of soil moisture on precipitation and on whether or not a crop is grown, the fallowing/planting problem is necessarily dynamic in nature. Consequently, the economic value of seasonal-precipitation forecasts in this situation is evaluated using a dynamic decision-making model. Burt and Allison (1963) and Burt and Johnson (1967) also took into account the dynamic nature of the fallowing/planting problem, but they did not consider the use of forecasts. More recently, Kennedy (1981) provides a summary of many applications of dynamic decision-making models in agriculture. Other studies of the value of weather information that involve dynamic decision-making situations include the fruit-frost problem (Katz et al., 1982) and the so-called dynamic cost-loss ratio problem (Murphy et al., 1985).

The fallowing/planting decision-making model is applied to two locations in the northern United States' Great Plains—Havre, Montana, and Williston, North Dakota. Characteristics of the model employed in the case study are described in Section 2, and some results of this study are reported in Section 3. Section 4 contains some concluding remarks.

[1] Department of Atmospheric Sciences, Oregon State University, Corvallis, OR 97331. Address: Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, CO 80307.

[2] Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, CO 80307. NCAR is sponsored by the National Science Foundation.

[3] Department of Atmospheric Sciences, Oregon State University, Corvallis, OR 97331.

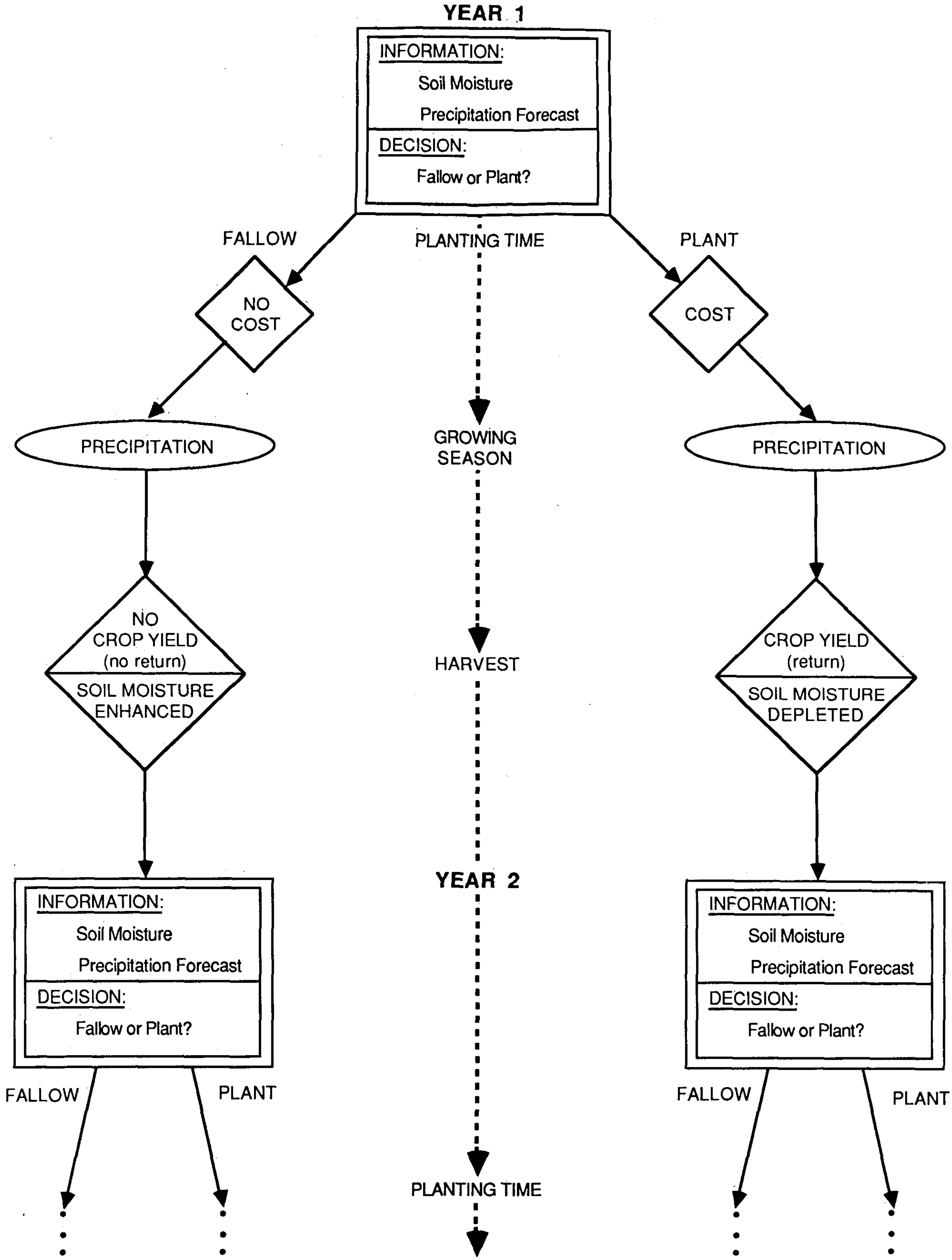


FIG. 1. Schematic diagram describing the sequential and dynamic nature of the fallowing/planting problem. See text for discussion.

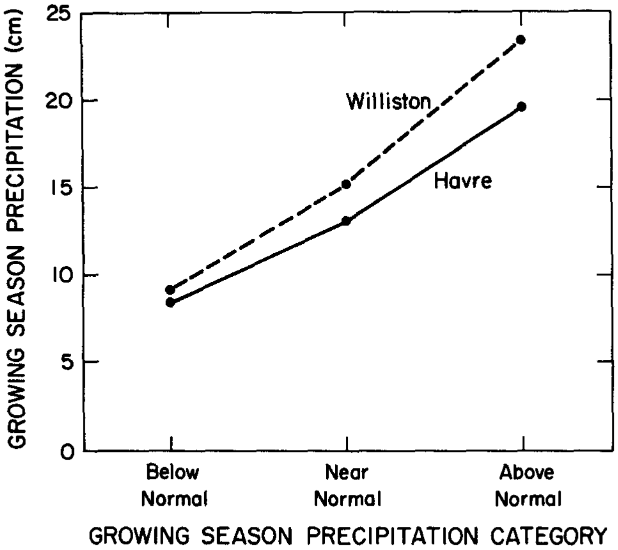


FIG. 2. Values of the categories of growing-season precipitation (May-July) for Havre, Montana, and Williston, North Dakota.

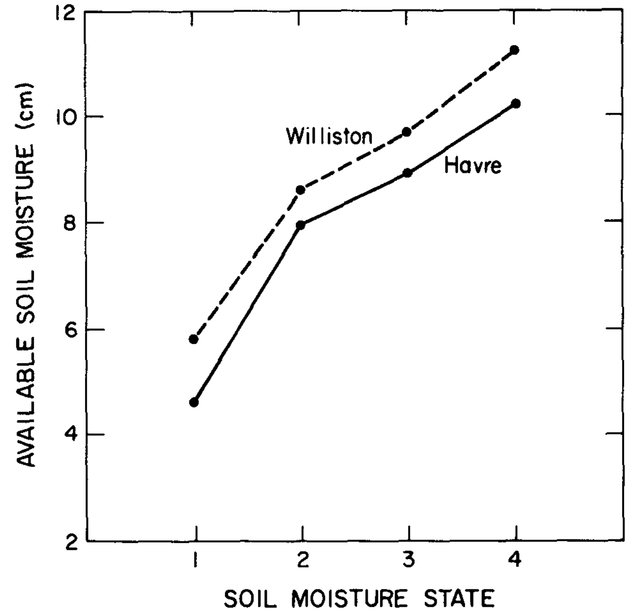


FIG. 3. Four states of available soil moisture at planting time for Havre, Montana, and Williston, North Dakota.

2. Fallowing/planting decision-making problem

a. General description of model

Figure 1 is a schematic diagram describing the fallowing/planting problem. Each year before planting time (about mid spring in the northern Great Plains), the decision maker—a farmer—must decide whether to fallow his land or to plant a spring-wheat crop. The farmer makes this decision on the basis of the soil moisture at planting time and some type of information about the amount of precipitation that will occur during the growing season. This information might simply be the climatological probabilities associated with various precipitation amounts, or it might be an actual forecast of growing-season precipitation such as the seasonal forecasts that are currently issued by the NWS. The farmer's decision affects both the return that he will receive in the current year and the amount of soil moisture that will be available the following year. For example, if a crop is planted the farmer will incur the cost of planting the crop, but he will also receive a return from the sale of the crop. In addition, the soil moisture will be depleted by growing the crop. On the other hand, if the land is fallowed, the farmer will neither incur a cost nor receive a return. However, the soil moisture should normally increase during the fallow period, leading to higher yields the following year.

Consequently, the fallowing/planting problem requires a dynamic decision-making model. Specifically, our model allows next year's soil moisture at planting time to depend on whether or not a crop is planted this year, on this year's soil moisture at planting time, and on the precipitation in the forthcoming growing season (Matthews and Army, 1960). The fallowing/planting model keeps track of the soil moisture at planting time each year, and we refer to this quantity as the "state variable" (or "state") of the decision-making process.

We define three categories of growing-season precipitation (May–July), corresponding to those currently used in NWS seasonal-precipitation forecasts: 1) below normal (signifying the lower 30 percent of the distribution of growing-season precipitation), 2) near normal (signifying the middle 40 percent of the distribution), and 3) above normal (signifying the upper 30 percent of the distribution). These categories are represented by the 0.15th, 0.50th (median), and 0.85th quantiles of the distribution of growing-season precipitation, respectively. Figure 2 contains the values of growing-season precipitation at Havre, Montana, and Williston, North Dakota—the two locations considered in the case study—for each of the three categories. These values are based on long-term climatic data at the respective sites (1942–1979 for Havre; 1951–1980 for Williston) and they were obtained for Williston from the NWS Climate Analysis Center (D. L. Gilman, personal communication) and for Havre from distributions of growing-season precipitation presented in Brown et al. (1981). As shown in Fig. 2, Williston typically has a somewhat wetter growing season than Havre.

For simplicity, only four states of available soil moisture are allowed, and their values for Havre and Williston are indicated in Fig. 3. These values are based on accepted assumptions regarding the use of soil moisture by a spring-wheat crop and the storage of non-growing-season and fallow-year precipitation as available soil moisture (Haas and Willis, 1962; Lehane and Staple, 1965; Matthews and Army, 1960). They represent the soil moisture to a depth of approximately 122 cm (four feet). It is of interest to note that available soil moisture is also higher at Williston than at Havre, corresponding to the difference in precipitation amounts noted earlier.

Table 1 illustrates the dependence of the soil-moisture state next year on the soil moisture, growing-season precipitation, and action taken this year. We assume that a wheat crop consumes all available moisture. Hence, if a crop is

TABLE 1. Soil-moisture state at planting time next year, given the soil-moisture state and growing-season precipitation this year, when the land is fallowed this year. The soil-moisture state next year is always State 1 when a crop is grown this year.

	Soil-moisture state next year		
	Precipitation category this year		
Soil-moisture state this year	Below normal	Near normal	Above normal
1	2	3	4
2	4	4	4
3	4	4	4
4	4	4	4

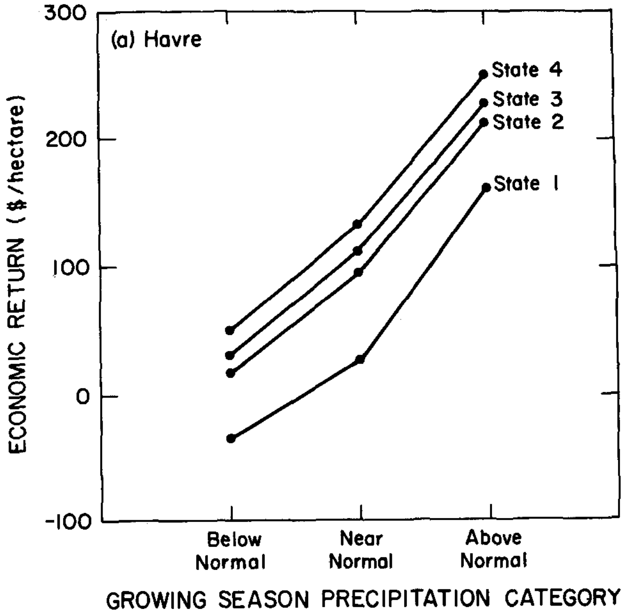
grown this year the soil-moisture state next year will be the lowest state, regardless of the amount of growing-season precipitation or the soil-moisture state this year. On the other hand, if the land is fallowed this year, the soil moisture will increase so that the state next year will be higher than this year (unless the soil-moisture state this year is already the highest state).

Spring-wheat yield is assumed to depend on the soil moisture at planting time and the growing-season precipitation (Baier, 1972). The use of these two variables attempts to mimic the information available, at least potentially, to the farmer (Brown et al., 1981). Other meteorological variables such as growing-season temperature are related to yields, but are less important in the region of concern and are ignored for the purposes of this study. Biological factors, such as plant pests, are also ignored. Although the relationship between wheat yields and weather variables is actually somewhat nonlinear, we assume, as a reasonable approximation, a linear relationship. In particular, spring-wheat yield is expressed as

$$Y = -873.4\ [\mathrm{kg/ha}] + 119.0\ [\mathrm{kg/(ha\ cm)}] \times R + 105.8\ [\mathrm{kg/(ha\ cm)}] \times M, \quad (1)$$

where Y is the expected yield in kg/hectare, R is growing-season precipitation in cm, and M is soil moisture at planting time in cm. This equation reproduces the yield table presented in Brown et al. (1981).

To determine the monetary payoffs that enter into the farmer's decision as to whether to fallow or to plant, several economic parameters must be specified. These parameters include the price that a unit of harvested spring wheat will receive, the production costs in raising a crop (which are assumed to be incurred only if a crop is actually planted), and a discount factor. For this case study, we let the crop price equal \$0.15 per kilogram (\$4 per bushel) and the cost of growing a crop equal \$126 per hectare (\$51 per acre), according to 1983 estimates adjusted from 1980 values (USDA, 1981). This value of the cost is assumed to include all of the typical expenses associated with growing a spring-wheat crop (e.g., seed, fertilizer, labor). The immediate return in dollars per hectare associated with growing a crop is then equal to the yield per hectare multiplied by the crop price, minus the cost of growing the crop, ignoring any effects that changes in production might have on price. The immediate return when the land is fallowed is always zero, since we ignore any costs or



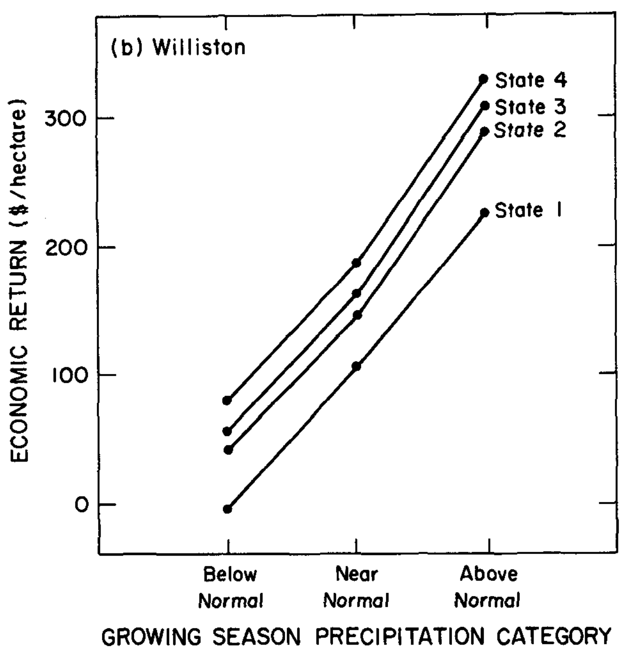


FIG. 4. Immediate economic returns (1983 dollars) for a) Havre, Montana, and b) Williston, North Dakota.

returns associated with fallowing. Such costs may arise, for example, from extra tillage that might be required.

The values of the immediate returns realized from growing a crop, for all combinations of soil-moisture states and precipitation categories, are presented in Fig. 4. It is interesting to note that these returns are always positive, except for the case in which a crop was grown the year before (i.e., soil-moisture State 1) and below-normal growing-season precipitation occurs in the current year.

The discount factor arises because economic considerations make it appropriate to weight returns in future years proportionately less than those in the current year. For example, future returns cannot be invested until they are actually received, and thus are not worth as much now as this year's returns. The discount factor used in the case study is 0.90. This value was chosen to reflect a 1983 interest rate of approximately 11 percent.

b. Climate information

Three types of climate information are of interest for the case study: climatological information, imperfect climate forecasts, and perfect information.[4] The methodology employed to solve the fallowing/planting decision-making problem has the advantage that the value of any, perhaps hypothetical, improvements in forecasts of growing-season precipitation can be estimated as well. Specifically, we consider several levels of improvements over current NWS forecasts. We assume that the forecasts are completely reliable (see Murphy and Daan [1985]).

1) *Climatological information.* In accordance with the three categories of growing-season precipitation defined in Section 2a, the climatological probability distribution of growing-season precipitation is specified as

$$\begin{aligned} \Pr\{\text{below normal}\} &= 0.3, \\ \Pr\{\text{near normal}\} &= 0.4, \\ \Pr\{\text{above normal}\} &= 0.3. \end{aligned} \tag{2}$$

This distribution, together with the quantiles presented in Fig. 2, constitutes the climatological information (in the same form as the NWS seasonal forecasts) that is available to spring-wheat farmers.

2) *Imperfect forecasts.* Two types of probability distributions are required to specify the characteristics of imperfect forecasts of growing-season precipitation: a) the conditional distributions of growing-season precipitation given the individual forecasts, and b) the frequency-of-use distribution of the individual forecasts, also called the predictive distribution. The conditional distributions specify how the probability of a particular precipitation category varies as a function of the forecast. These conditional probabilities can be thought of as replacements for the (unconditional) climatological probabilities. The predictive distribution simply indicates how frequently individual forecasts are made. Roughly speaking, the greater the dispersion of this predictive distribution for reliable forecasts, the higher the quality of the forecasts. For example, higher quality forecasts would generally include more frequent forecasts of extreme events.

The conditional and predictive distributions for current imperfect seasonal-precipitation forecasts are presented in Fig. 5. The conditional distributions are illustrated in the individual diagrams, whereas the percentages in parentheses in the five diagrams constitute the corresponding predictive probabilities. These distributions, for five distinct forecasts, are condensed from seasonal-precipitation forecasts issued by the NWS, and are based on 16 forecasts pooled over all seasons and over 96 stations within the United States (1536 cases total).

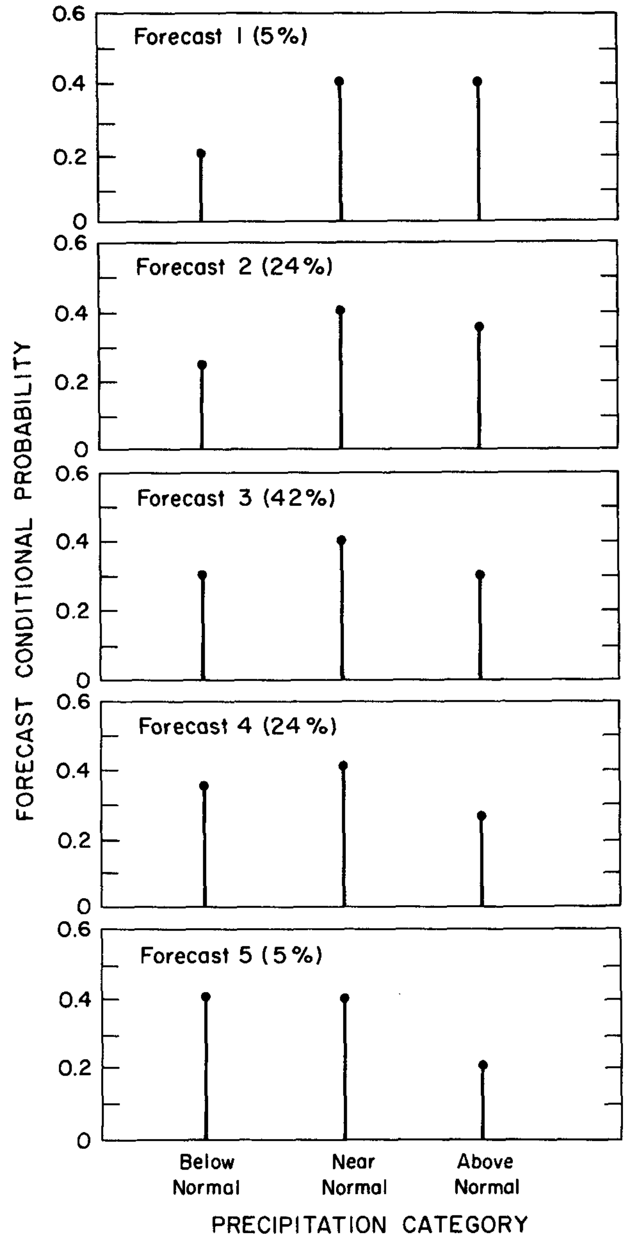


FIG. 5. Conditional distributions of actual NWS seasonal-precipitation forecasts. Relative frequency of use for each forecast is indicated in parentheses.

As an example of the interpretation of the conditional and predictive distributions, consider Forecast 1 in Fig. 5. As shown in parentheses, this forecast is made on only five percent of the forecasting occasions. Furthermore, when Forecast 1 is used, the forecast probability of below-normal seasonal precipitation is 0.20, the forecast probability of

[4] In this section and the remainder of this paper, we use the terms *climate information* and *climatological information,* and it is important to distinguish between these two types of information. By climatological information we simply mean information that is based solely on long records of weather and climate data (e.g., climatological probabilities). On the other hand, climate information is a generic term referring to various types of information, including (for example) climatological information and climate forecasts.

near-normal precipitation is 0.40, and the forecast probability of above-normal precipitation is also 0.40.

Note that the conditional probability of near-normal precipitation is a constant, 0.40, for all forecasts in Fig. 5, according to the constraint placed on actual NWS seasonal-precipitation forecasts. Also note that 42 percent of the time the conditional distribution is identical to the climatological distribution, implying that in these cases the forecast provides the decision maker with no more information than that provided by the climatological probabilities. The seasonal-precipitation forecasts issued by the NWS are described in more detail by the Climate Analysis Center (1983).

3) *Perfect information.* In the case of perfect information, 30 percent of the time it is known that below-normal precipitation will occur, 40 percent of the time it is known that near-normal precipitation will occur, and 30 percent of the time it is known that above-normal precipitation will occur. These frequencies constitute the predictive distribution for perfect information. Thus, perfect information consists of a set of forecasts in which the conditional probabilities are all zeroes and ones and the predictive distribution is equivalent to the climatological distribution. Although it is extremely unlikely that perfect seasonal-precipitation forecasts will ever be available, perfect information serves as a useful upper bound on the value of imperfect forecasts.

4) *Improved forecasts.* Improved seasonal-precipitation forecasts are of interest because we expect that climate research may lead to improvements in the quality of such forecasts in the relatively near future (see Gilman [1985] and Namias [1985] for discussions of the prospects for future improvements in these forecasts). Thus it is of interest to evaluate the potential increase in economic value associated with hypothetical improvements in the quality of imperfect climate forecasts. For the case study, the forecast improvements are purely hypothetical and are defined in a somewhat arbitrary manner.

Specifically, we have devised a set of six levels of improved forecasts, intermediate in quality between current forecasts and perfect information. The forecasts corresponding to the first five levels of improvement represent very simplified forecasts that are of the same form as current forecasts—that is, the probability associated with near-normal precipitation is 0.40 in each case. The fifth level of improvement corresponds to the best forecasts that can be produced while maintaining this structure, and we refer to these forecasts as "pseudo-perfect" forecasts. The sixth level of improvement actually represents a set of improvements intermediate in quality between pseudo-perfect forecasts and perfect information. This additional level of improvement involves relaxing the constraint that near-normal precipitation is always assigned a forecast probability of 0.40.

c. Forecast value and quality

We assume that the farmer's goal is to maximize the return from his land over a long period of time—say, his lifetime. More precisely, his goal is to maximize the total expected discounted return over the indefinite future. We will refer to *maximal total expected discounted return* as simply *expected return.* The term *expected* refers to a probability-weighted average, an operation necessitated by the fact that actual returns are dependent upon the forthcoming growing-season precipitation and the only information available about these precipitation events is in the form of probabilities.

TABLE 2. Maximal total expected discounted (0.90 discount factor) return of climatological information (RC), and economic value of current forecasts and perfect information (VF and VP) at Havre, Montana, and Williston, North Dakota (1983 dollars).

Location	RC ($/hectare)	VF ($/hectare)	VP ($/hectare)	VF/VP × 100 (%)
Havre	580.55	10.08	196.62	5.1
Williston	1139.65	0.00	116.09	0.0

In order to meet his goal of maximizing the expected return from his land, the farmer would follow a particular strategy of fallowing or planting, depending on the level of soil moisture at planting time and the forecast of growing-season precipitation. A rule that specifies this strategy is called the *optimal policy.* Finding the optimal policies and expected returns for the various types of climate information is a difficult mathematical problem because of the dynamic nature of the fallowing/planting decision-making situation. (See Brown et al. [1985] or Katz et al. [1986] for a discussion of how this optimization problem is solved.)

Our objective is to estimate the economic value of current, as well as hypothetically improved, forecasts of growing-season precipitation in the fallowing/planting decision-making problem. It is natural to measure the value of any information, such as forecasts, relative to the situation in which the information is not available (e.g., Winkler and Murphy, 1985). In this regard, information (e.g., forecasts) is only of value insofar as it leads to an optimal policy that differs from the optimal policy that would be followed without the information.

For this case study, it is reasonable to assume that climatological probabilities of growing-season precipitation would always be available. In fact, tables of such probabilities are provided for use by farmers in Brown et al. (1981). Thus, the *value* of current and improved growing-season precipitation forecasts is measured as the net increase in expected return for such forecasts over the expected return based on climatological information alone. It is important to note that the relationships among the expected returns are such that the economic value of perfect information is greater than or equal to the economic value of imperfect forecasts.

It is of interest to examine changes in forecast value in relation to changes in forecast quality. To conduct such an examination, we need an objective index of forecast quality. A reasonable index in this case is the total variance of the predictive distribution of the probabilistic forecasts. This measure can be viewed as the average distance between the vector of probabilistic forecasts assigned to the weather states and the corresponding vector of climatological probabilities. It is a reasonable index because the quality of reliable forecasts, defined in a generally acceptable manner, should increase monotonically with increasing variance. Perfect information has the highest variance. On the other hand, climatological information has zero variance, since this information can be viewed as a special case of climate forecasts in which the same forecast is issued on each occasion; as a result, the predictive

TABLE 3. Optimal actions (F = fallow, P = plant) for different types of information at Havre, Montana, as a function of current soil-moisture state.

Type of information	Probabilities assigned to precipitation states: Below normal	Near normal	Above normal	Optimal action: Current soil-moisture state 1	2	3	4
Climatological information	0.30	0.40	0.30	F	P	P	P
Perfect information	0.00	0.00	1.00	P	P	P	P
	0.00	1.00	0.00	F	P	P	P
	1.00	0.00	0.00	F	F	F	F
Current forecasts	0.20	0.40	0.40	P	P	P	P
	0.25	0.40	0.35	P	P	P	P
	0.30	0.40	0.30	F	P	P	P
	0.35	0.40	0.25	F	P	P	P
	0.40	0.40	0.20	F	P	P	P

distribution is degenerate. Thus, we can measure quality on a relative scale between climatological and perfect information by dividing each forecast variance by the variance of perfect information. On this scale, climatological information has zero percent quality and perfect information has 100 percent quality. Current forecasts have a relative quality of 0.5 percent, and the relative quality values for improved forecasts lie between this value and 100 percent (see Fig. 6).

3. Some results of case study

The expected return of climatological information (RC) and the economic values of current forecasts and perfect information (VF and VP, respectively) for Havre and Williston are presented in Table 2. As would be anticipated due to the differences in precipitation at Havre and Williston and the positive relationship between wheat yields and precipitation (see eq. [1]), the expected return with climatological information alone is higher at Williston than at Havre. The value of current imperfect climate forecasts is a modest \$10/hectare at Havre. The quality of current seasonal-precipitation forecasts, together with the higher growing-season precipitation at Williston (vis-a-vis Havre), is such that it is *never* optimal to fallow at that location; the same optimal policy as with climatological information alone. Thus, current forecasts have no value at Williston. On the other hand, perfect information is of considerable value (greater than \$100/hectare) at both Havre and Williston. The entries in the last column in Table 2 indicate the ratio of VF to VP expressed in terms of percent. In particular, the value of current forecasts at Havre is only slightly more than 5 percent of the value of perfect information. Note that this percentage is approximately 10 times greater than the relative quality of current forecasts.

Optimal actions associated with use of the various types of climate information at Havre are listed in Table 3. In general, the optimal policy is to plant a crop unless the current soil-moisture state is the driest state or the forecast assigns a relatively high probability to the occurrence of below-normal precipitation. Note that the use of climatological information leads to fallowing and planting in alternate years, since the soil-moisture dynamics are such that planting always leads to the lowest soil-moisture state the next year and since fallowing leads to a higher soil-moisture state (see Table 1).

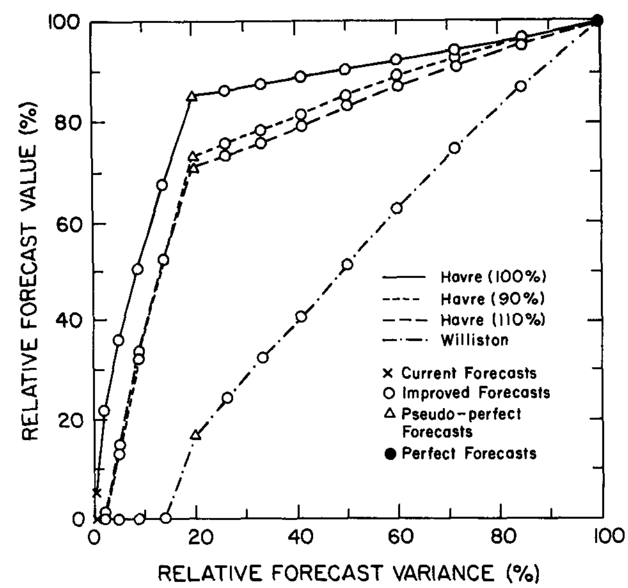


FIG. 6. Relationships between forecast value and quality for Havre, Montana, and Williston, North Dakota, including two cases of climate change at Havre (90 percent and 110 percent). Havre (100 %) signifies current climatology at Havre.

The modest positive value of current forecasts at Havre results from the fact that in soil-moisture State 1 it is optimal to plant rather than fallow whenever there is a relatively low probability (0.20 or 0.25) of below-normal precipitation. With perfect information, it is optimal to fallow whenever the growing-season precipitation is expected to be below normal or, in soil-moisture State 1, near normal. It can be shown that the optimal policy at Havre with perfect information involves planting in half of the years on the average as is also the case with climatological information (Katz et al., 1986). Thus, the value of perfect information comes not through growing a crop more often, but simply through the advantage of planting in those years known to be relatively wet.

The sensitivity of the results to the price of spring wheat was also investigated. It was found for Havre that when the price of wheat reaches \$0.18 per kilogram (\$5.00 per bushel) or more, current forecasts have no value because planting a crop every year is then optimal with both these forecasts and climatological information. On the other hand, decreases in wheat price (from \$0.15 per kilogram [\$4.00 per bushel]) at Havre are associated first with sharp decreases and then with modest increases in forecast value. It is also of interest to note that forecasts of the current quality would have a small positive value at Williston (rather than zero value as is currently the case) if the price of wheat fell to \$0.07 per kilogram (\$2.00 per bushel).

RC, VF, and VP were also computed for nine other stations in eastern Montana and western North Dakota. Current forecasts were found to have little or no value at these locations, whereas the value of perfect information ranged as high as \$205 per hectare at Jordan, Montana. The maximum value taken on by RC was \$1200 per hectare at Plevna, Montana, the wettest of the stations considered.

An analytical expression was derived for the climatic break-even point at which it is optimal to continuous crop rather than alternate fallow using climatological information alone (Katz et al., 1986). Using this expression, it was found that an increase in expected growing-season precipitation at Havre from the current value of 13.6 cm (5.34 inches) to 14.1 cm (5.54 inches) or above would lead to planting a crop every year as the optimal policy using climatological information alone. Similarly, Baier (1972) found that it is optimal to continuous crop rather than alternate fallow spring wheat when the expected growing-season precipitation equals 15.6 cm (6.14 inches) in an adjacent region within Saskatchewan. These results appear to conflict with the policy of alternate fallowing practiced by at least some spring-wheat farmers in the relatively wetter areas of the northern Great Plains.

The relationships between the quality and value of current forecasts, the improved forecasts described in Section 2b, and perfect information are presented in Fig. 6 for Havre and Williston. Figure 6 also includes two cases of climate change at Havre, in which the climatological precipitation distribution was altered to 90 percent and 110 percent of current values. These changes were accomplished by adjusting the mean growing-season precipitation while keeping the differences between the quantiles proportionately the same. The value scale (relative value) in Fig. 6 is the forecast value VF standardized by the value of perfect information VP, expressed in percent: (VF/VP) $\times$ 100. Hence, perfect information has 100 percent value, whereas climatological information has zero percent value.

The curves in Fig. 6 indicate that any improvements in the quality of the forecasts would result in rapid increases in the value of the forecasts at Havre. On the other hand, the forecasts would have to approach the level of pseudo-perfect forecasts before they would be of any value at Williston. It is of interest to note that the three curves for Havre have a shape that is quite different from the shape of the curve for Williston. The kink in the curves at the point corresponding to pseudo-perfect forecasts may be an artifact of the specific manner in which the forecasts were improved.

4. Concluding remarks

We have described the application of a dynamic decision-making model to the problem of whether a spring-wheat farmer in the northern Great Plains should fallow his land or plant a crop. The results of the case study indicate that 1) current NWS seasonal-precipitation forecasts have, at most, minimal economic value in the context of this problem; 2) perfect seasonal-precipitation forecasts would have considerable value; and 3) in some cases, relatively modest improvements in the quality of the forecasts would result in large increases in value. Moreover, the relationship between forecast quality and forecast value is quite sensitive to precipitation climatology.

The model employed in this case study of the fallowing/planting problem makes certain assumptions and simplifications regarding spring-wheat farmers' decision-making procedures. For example, farmers consider factors such as salinity, soil fertility, pests, and erosion, in addition to soil moisture, in deciding whether to fallow or plant a crop. Simplifying assumptions made in specifying the soil-moisture dynamics and precipitation climatology also impose some limitations on the results of this case study. For example, a larger number of soil-moisture states and more complex soil-moisture dynamics coupled with a more complete precipitation climatology might provide a better representation of the physical factors that are important in growing spring wheat.

With regard to the decisions made by spring-wheat farmers, it may be of interest to investigate the way the farmers *actually* use (or would use) climatological information and imperfect climate forecasts in deciding whether to fallow their land or plant a crop. A complementary descriptive analysis of this type was employed in the fruit-frost study to examine the decisions actually made by orchardists on the basis of frost forecasts (Stewart et al., 1984). In the future, it would also be useful to consider more realistic approaches to modeling farmers' attitudes toward risk. In this study, we assumed that the farmers are risk neutral (i.e., have a linear utility function), whereas a nonlinear utility function that realistically models the farmers' levels of risk aversion would be more appropriate (e.g., Winkler and Murphy, 1985). In addition, we have considered only the decisions made by an individual farmer, whereas in order to determine the total value of climate forecasts, it would be necessary to evaluate decisions made by all spring-wheat farmers simultaneously.

With regard to the value of seasonal-climate forecasts, it would be of interest in the future to examine the economic value of seasonal-temperature forecasts. Since these forecasts generally are considered to be more skillful than seasonal-precipitation forecasts, they may also have greater economic value. The energy and agricultural industries represent two possible areas for a case study of the use and value of seasonal-temperature forecasts.

Acknowledgments. We would like to thank Donald L. Gilman for providing the data necessary to derive the conditional and predictive probability distributions of current NWS seasonal-precipitation forecasts. We also would like to express our appreciation to Joseph M. Caprio, John W. Enz, and Daniel S. Wilks for their assistance in obtaining and evaluating data needed to apply the dynamic decision-making model to the fallowing/planting problem.

This research was supported in part by the National Oceanic and Atmospheric Administration (Climate Analysis Center) under grant NA82AA-D-00042 and by the National Science Foundation (Division of Atmospheric Sciences) under grants ATM-8209713 and ATM-8507495.

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